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Memo

DATE: April 20, 2007

TO: RHIC E-Coolers

FROM: Ady Herscovitch

SUBJECT: **Minutes of the April 20, 2007 Meeting**

Present: Ilan Ben-Zvi, Xiangyun Chang, Alexei Fedotov, Harald Hahn, Ady Herscovitch, Damayanti Naik, Thomas Roser, Gang Wang.

Topic discussed: Fermilab Collaboration Results and Simulations

Fermilab Collaboration Results and Simulations: Alexei gave a detailed update on the status of experimental electron beam cooling results that have been performed in the Fermilab recycler and their interpretation. The Fermilab electron beam Recycler cooler, which has been in operation since July 2005, is utilized to cool antiprotons with a 4.338 MeV electron beam that is generated in a Pelletron (with energy recovery). Results from this electron beam cooler are of significance to the RHIC electron beam cooler for two reasons:

1. All other electron beam coolers have electron beam energies that are lower than 400 kV. The Recycler 4.3 MeV electron beam is an important intermediate step to the 53 MeV electron beam needed for the RHIC electron beam cooler.
2. Cooling in the Fermilab electron beam Recycler is the only non-magnetized electron beam cooling in the world.

As such, this cooler offers the best venue for testing theoretical models and simulations, on which the RHIC electron beam cooler is based. Therefore, Alexei has been collaborating with Lionel Prost and Alexander Shemyakin from Fermilab as well as with Anatoly Sidorin (JINR Dubna Russia) in a series of cooling experiments and their theoretical interpretation.

Studies and issues to be resolved were: Benchmarking of non-magnetized friction force. Fitting unknown parameters of the electron beam such as transverse angular spread of electrons. Saturation of friction force value/drag rate with electron beam current, and magnitude of transverse cooling. Measurements performed were longitudinal friction force (i.e., drag rate), as well as longitudinal and transverse cooling. Theoretical considerations involved 1-D and 3-D representation of the non-magnetized friction force and the effect of taking the Coulomb Logarithm (which has velocity dependence) outside or inside the integral over electron velocity distribution. Basically, to expedite simulations, the Coulomb Logarithm was taken outside the velocity integrals. This approximation allows using a 1-D representation for shorter simulation running time. The experimentally measured longitudinal friction force fitted well with the non-magnetized force expression, and the resulting

parameters of the electron beam (electron density, transverse angular spread, longitudinal momentum spread) were also in reasonable agreement.

To Harald's question on whether the antiproton density was sufficient to have heating due to IBS Alexei answer was affirmative. Ilan began a discussion regarding the accuracy of the theory used in the comparison with experiments. To a question by Ilan regarding the error introduced by taking the Coulomb Logarithm outside the velocity integrals, Alexei confirmed that this simulation leads to an uncertainty, which could be as high as 45% for the Recycler case if the same beam parameters are used in both 3-D and 1-D simulations. But, in the case of RHIC the uncertainty will be only 10% - 15%. Ilan contented that for RHIC, a basis set of 3-D simulations should be done.

A seeming discrepancy, which failed to show increase in friction force with increase in electron beam current (at currents larger than 100 mA), was resolved. For a still unknown reasons, the electron density did not increase (and even decreased) with increase in electron beam current. Nevertheless, the friction force did increase with increasing electron beam density.

Measurements and simulations of diffusion and cooling have not shown quite as clear-cut an agreement as is the case with the friction force. One of the reasons may be due to the fact that transverse emittance is based on FW (Flying Wire), while longitudinal momentum deviation is based on Schottky. For parameters of electron beam which fit measured longitudinal friction force one gets good agreement between measured (with FW) and simulated transverse cooling, but in this case longitudinal cooling in simulations is overestimated. With addition of transverse velocity gradient agreement for longitudinal cooling is achieved, but this results in disagreement with transverse cooling measurement (based on FW).

From a discussion that ensued regarding this still unresolved issue, the discrepancy might be due to the fact that in longitudinal momentum deviation measurements (Schottky) the whole beam is measured, while in transverse emittance measurements (based on FW) full width at half maximum (FWHM) is measured. Since the distribution is not Gaussian, the discrepancy might be due to difference in measurement methods.

Below is Alexei's presentation

Alexei's Presentation

1

Update on studies of electron cooling in Recycler (FNAL)

L. Prost, A. Shemyakin (FNAL)

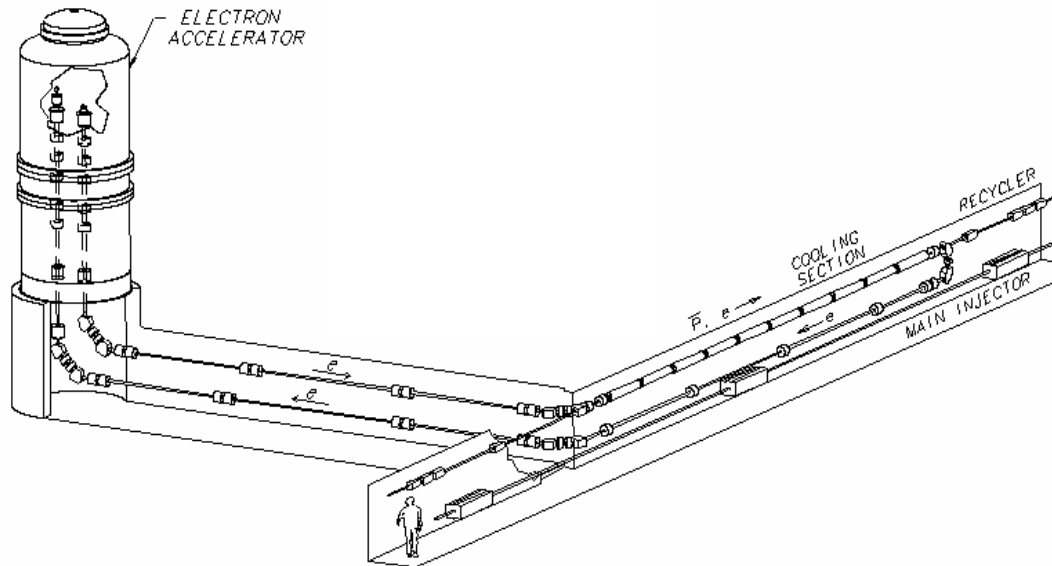
A. Fedotov (BNL), A. Sidorin (JINR)

April 20, 2007

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Fermilab Recycler electron cooler (in operation since July 2005)

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Electron energy	MeV	4.338
Beam current used for cooling	A	0.05 - 0.5
Magnetic field in CS	G	105
Beam radius in the cooling section	mm	2.5 - 5
Pressure	nTorr	0.2 - 1
Length of the cooling section	m	20

- Electrostatic accelerator (Pelletron) working in the energy recovery mode
- DC electron beam
- 100 G longitudinal magnetic field in the cooling section
- Lumped focusing outside the cooling section

FNAL electron cooler is the cooler with the highest electron energy up to date: 4.3 MeV (RHIC-II will be 53 MeV).

All other electron coolers operate at energies < 400 keV.

FNAL cooler is also the only cooler which is based on a principle of non-magnetized cooling (transverse temperature/angular spread of the electron beam is not suppressed by strong magnetic field in the cooling section). Weak magnetic field in the cooling section is only used to keep transverse angular spread in the cooling section at required level.

RHIC-II cooler – also based on non-magnetized cooling; also uses weak solenoids in cooling section to compensate space-charge angular spread.

Questions we were trying to study/resolve

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1. Benchmarking of non-magnetized friction force.
2. Fitting unknown parameters of the electron beam such as transverse angular spread of electrons.
3. Saturation of friction force value/drag rate with the current of electron beam.
4. Magnitude of transverse cooling.

As well as some more detailed effects in cooling process, such as:

- Spreading of beam profiles during drag rate measurements (requires also accurate estimate of velocity gradient, profile, etc.)
- Evolution of non-Gaussian beam profiles under Cooling+Diffusion;
- Benchmarking of our computer models.

Two type of measurements:

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1. Longitudinal Friction force (drag rate):

- measure longitudinal drag rate with the voltage jump method (for fixed current with different values of a jump); gives curve of friction force F vs. velocity (in PRF).
- measure dependence of drag rate (for a fixed jump value) on electron beam current

2. Study longitudinal and transverse cooling:

- measure diffusion rates for different current densities of anti-proton beam: to find out what contribution comes from gas-scattering, dampers, IBS.
- study cooling rates: both transverse and longitudinal for high intensities and low-intensities of anti-protons.

Recent measurements:

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December 2006:

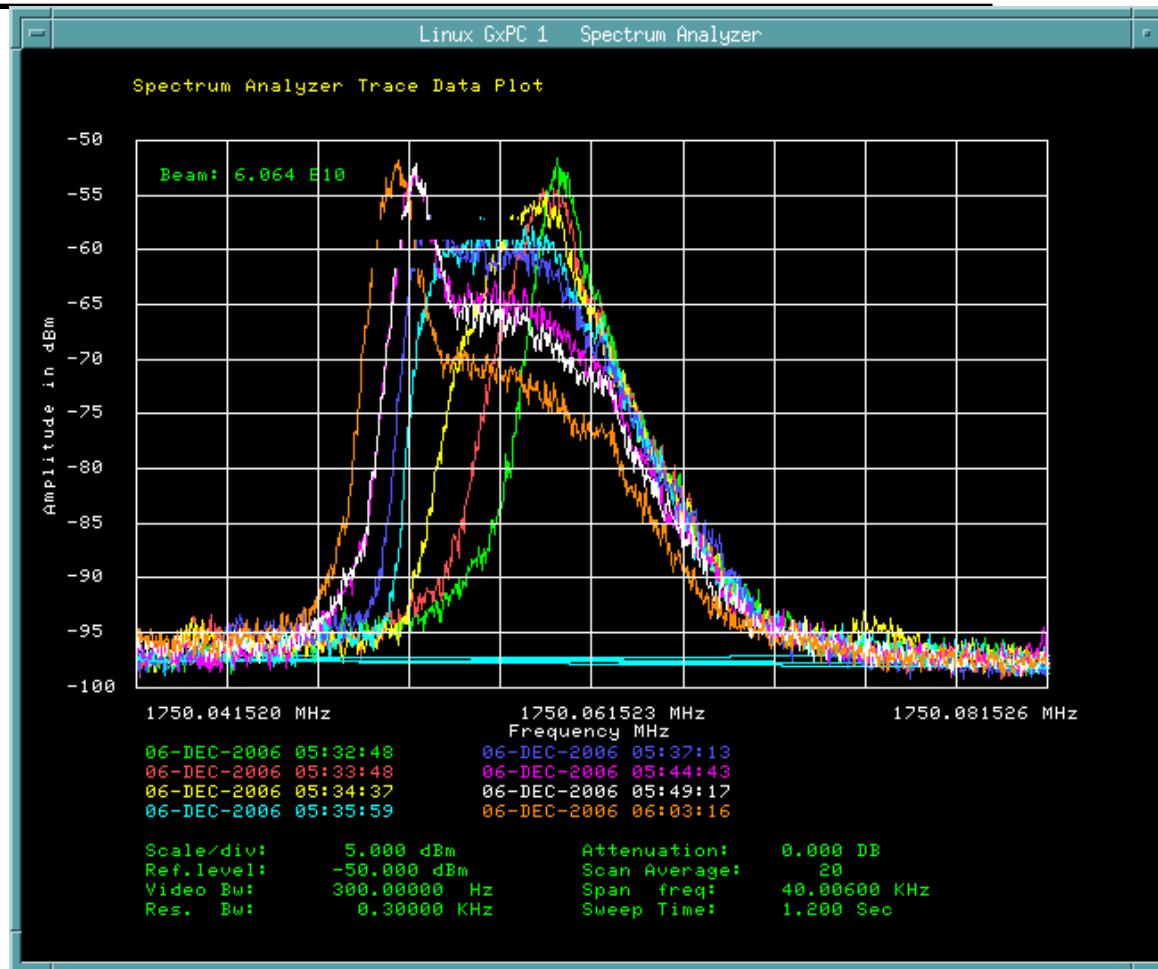
- 1) friction force measurements; current dependence of friction force.
- 2) diffusion/cooling measurements for low and high intensity pbar beams.

February-March 2007:

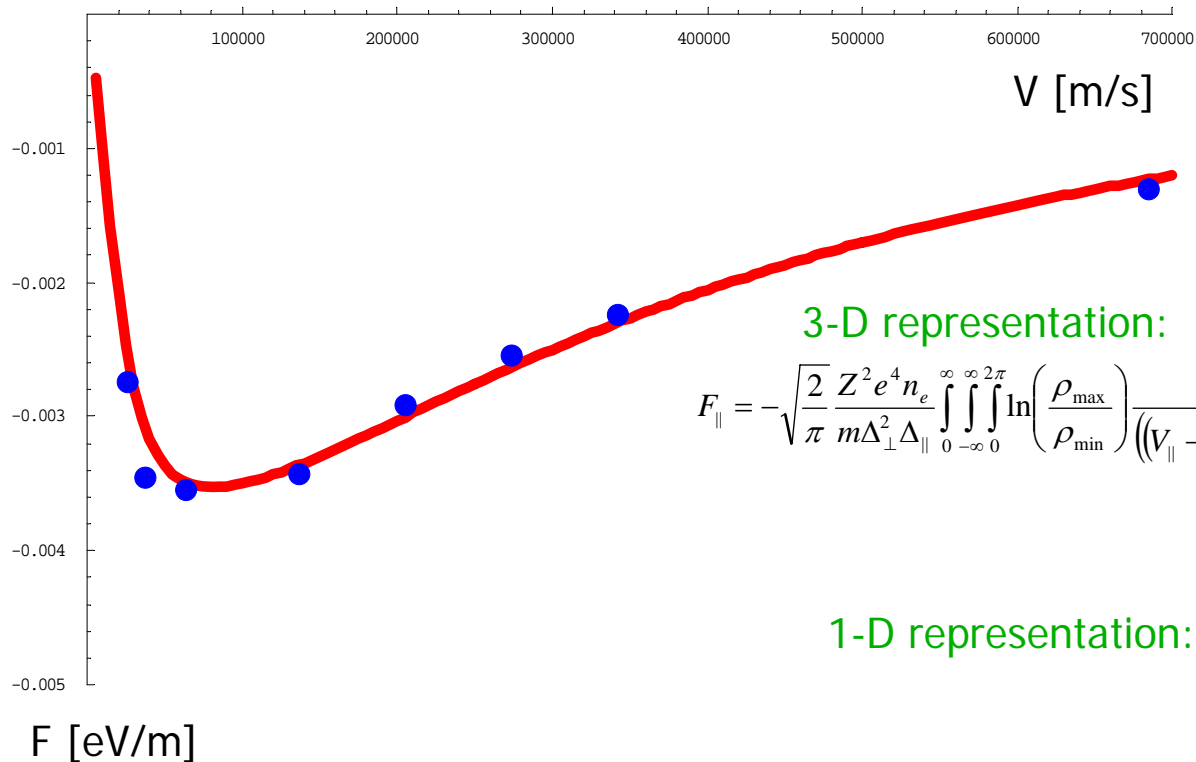
many diffusion/cooling measurements with low-intensity pbar beams. Measurements of Recycler lattice – calibration of FW emittance measurements.

**Benchmarking of non-magnetized
friction force expressions.**

Example of drag rate/force measurement (single point): Evolution of longitudinal distribution during the voltage jump (in Log scale) ⁹



Red curve - longitudinal friction force with LOG under the integral (3-D representation). Parameters: electron density $J_e=0.594 \text{ A/cm}^2$, transverse rms velocity spread $V_{\perp}=3.754 \text{ e5 m/s}$ (angles 130 e-6 rad), $V_{\parallel}=18000 \text{ m/s}$.
Blue dots - measurements.



3-D representation:

$$F_{\parallel} = -\sqrt{\frac{2}{\pi}} \frac{Z^2 e^4 n_e}{m \Delta_{\perp}^2 \Delta_{\parallel}} \int_0^{\infty} \int_{-\infty}^{\infty} \int_0^{2\pi} \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right) \frac{(V_{\parallel} - v_{\parallel}) \exp\left(-\frac{v_{\perp}^2}{2\Delta_{\perp}^2} - \frac{v_{\parallel}^2}{2\Delta_{\parallel}^2}\right)}{\left((V_{\parallel} - v_{\parallel})^2 + (V_{\perp} - v_{\perp} \cos \varphi)^2 + v_{\perp}^2 \sin^2 \varphi\right)^{3/2}} v_{\perp} d\varphi dv_{\parallel} dv_{\perp}$$

1-D representation:

$$F_{\parallel} = 2\sqrt{2\pi} \frac{n_e e^4 Z^2 L_C}{m} \frac{V_{\parallel}}{\Delta_{\perp}^3} \text{Int}_{\parallel}$$

$$\text{Int}_{\parallel} = \int_0^{\infty} \frac{\exp\left(-\frac{V_{\perp}^2}{2\Delta_{\perp}^2} \frac{1}{1+q} - \frac{V_{\parallel}^2}{2\Delta_{\parallel}^2} \frac{1}{(\Delta_{\parallel}/\Delta_{\perp})^2 + q}\right)}{(1+q)\left((\Delta_{\parallel}/\Delta_{\perp})^2 + q\right)^{3/2}} dq$$

Friction Force - Summary

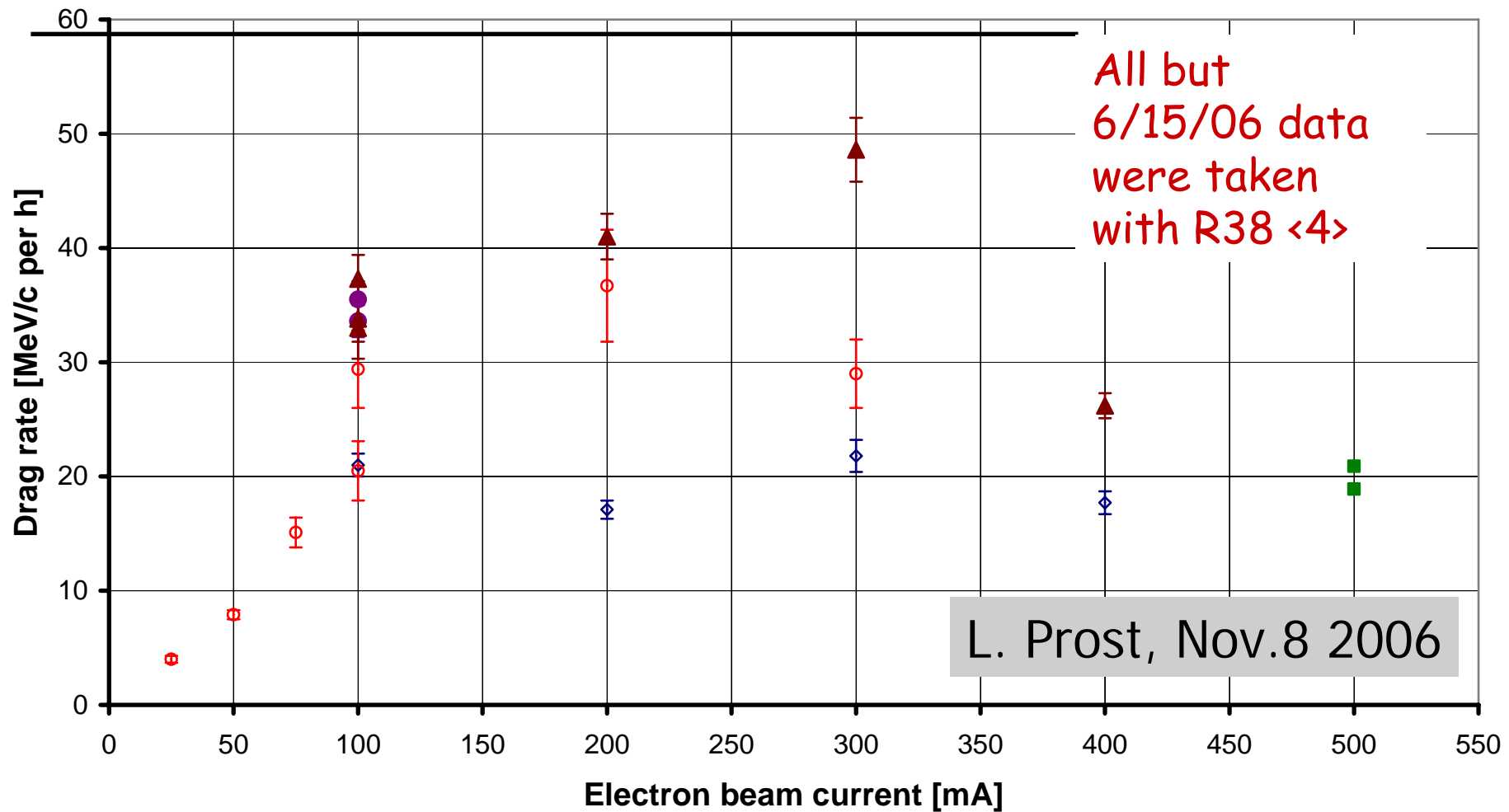
11

1. We studied 1-D vs 3-D representation of the non-magnetized friction force – good understanding of various questions.
2. Studied effect of Coulomb Logarithm outside vs Log inside the integral over electron velocity distribution.

Experimentally measured longitudinal friction force can be fitted with the non-magnetized force expression pretty well. Resulting parameters of the electron beam (electron density, transverse angular spread, longitudinal momentum spread) are reasonable.

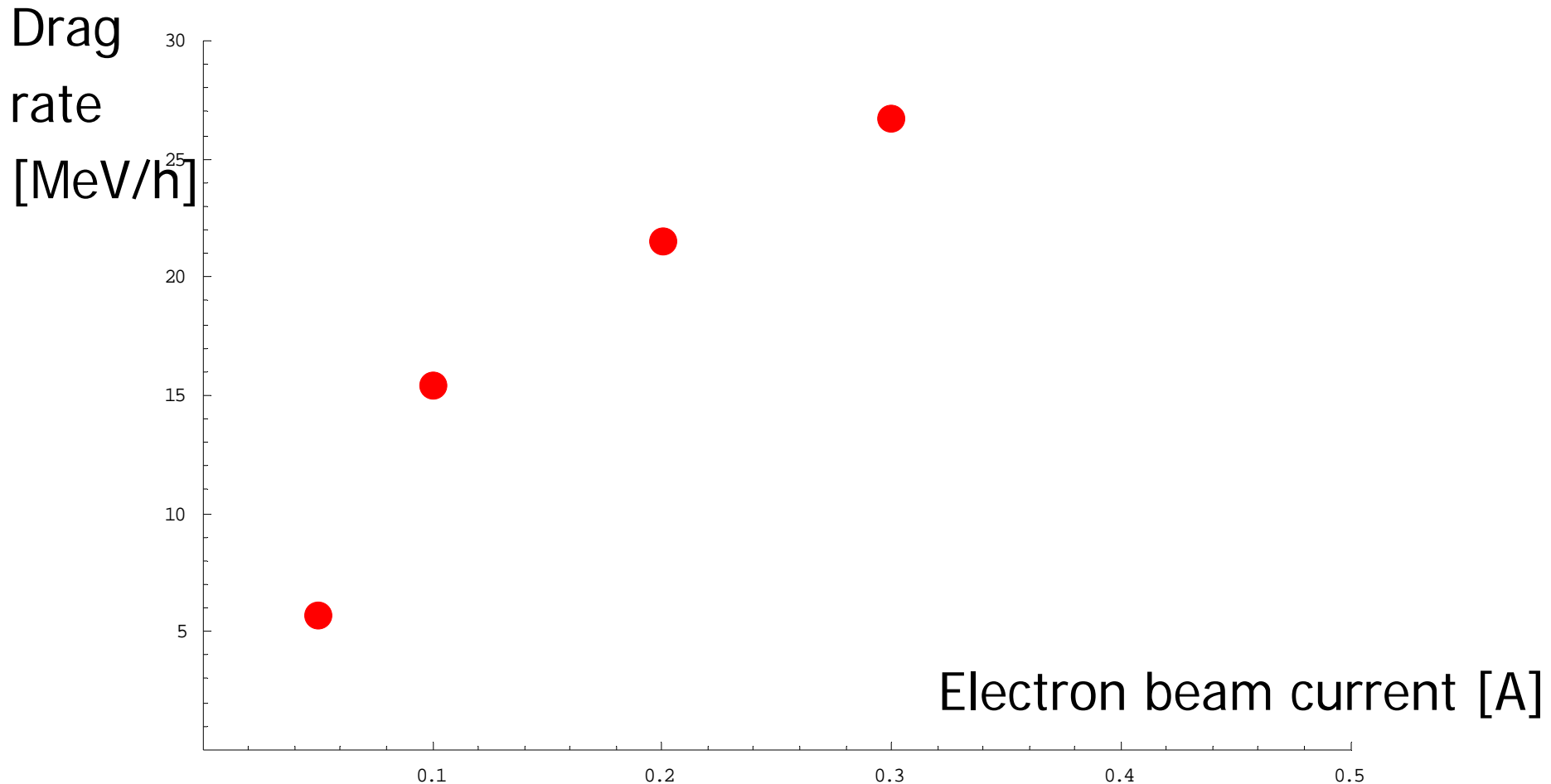
Friction Force: dependence on electron beam current

◇ 2/1/2006 ■ 'Older' ○ 6/15/2006 ● 11/01/06 'Realigned' ▲ 11/01/06 SPB01I = 14.5 A



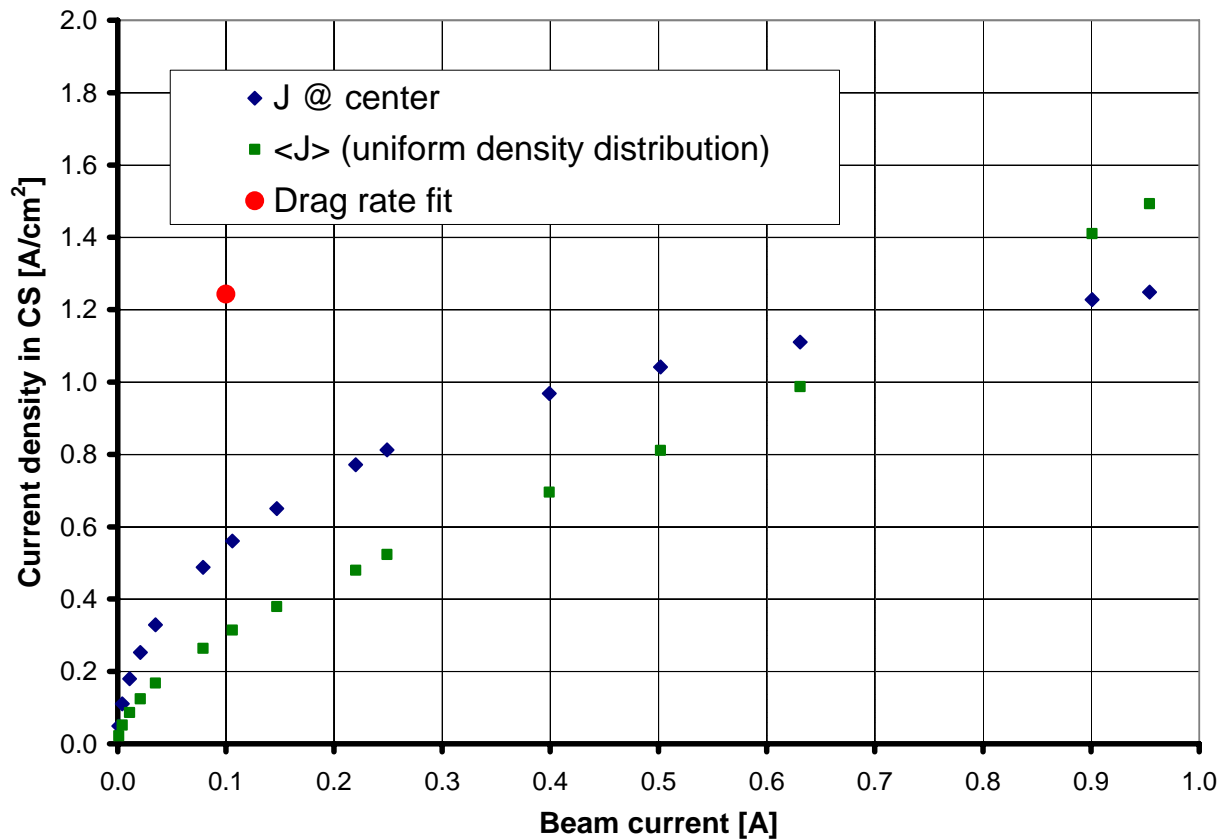
December 6, 2006 measurements – current dependence (for 5 keV jump)

14



Simulation of electron density (from L. Prost HB2006 May 2006 presentation)

15



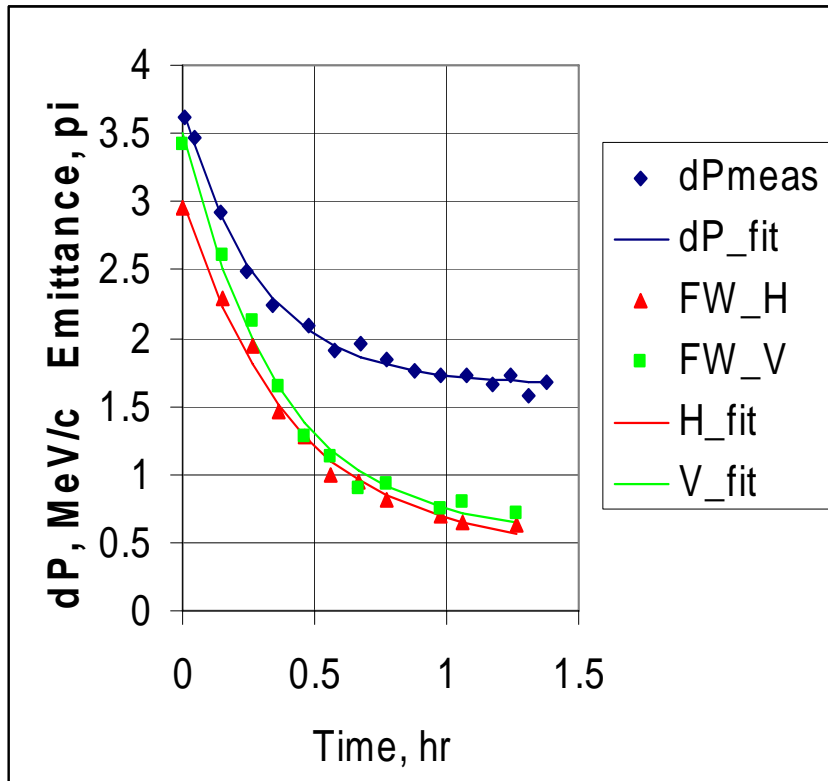
Friction Force current dependence - Summary

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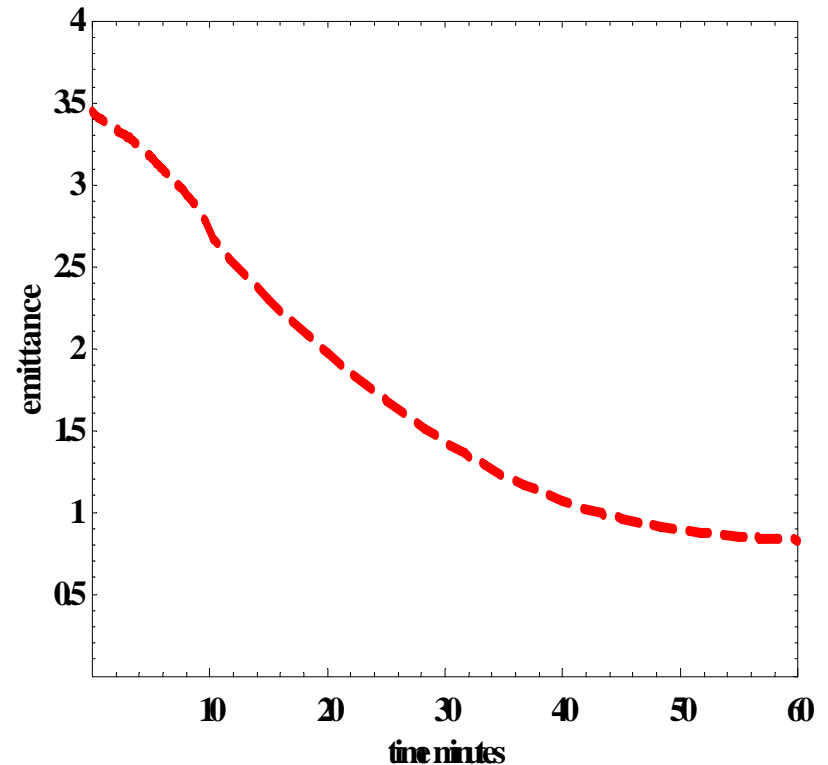
1. December 2006: Measurements were done for electron current of 100, 200, 300 mA – measured rate is in agreement with predicted based on simulated electron peak density.
2. Attempt to measure with 400 mA failed due to losses – some settings were changed trying to avoid losses – not successful.
3. Setting were returned back and drag rate was measured for 50 mA – however, some conditions were not the same anymore – measured rate did not agree with density predictions.

Diffusion and cooling measurements

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1. **Measure various contributions to diffusion.**
 2. **Understand amount of transverse cooling – strong (unexpected) transverse cooling is routinely observed following 2006 shutdown.**

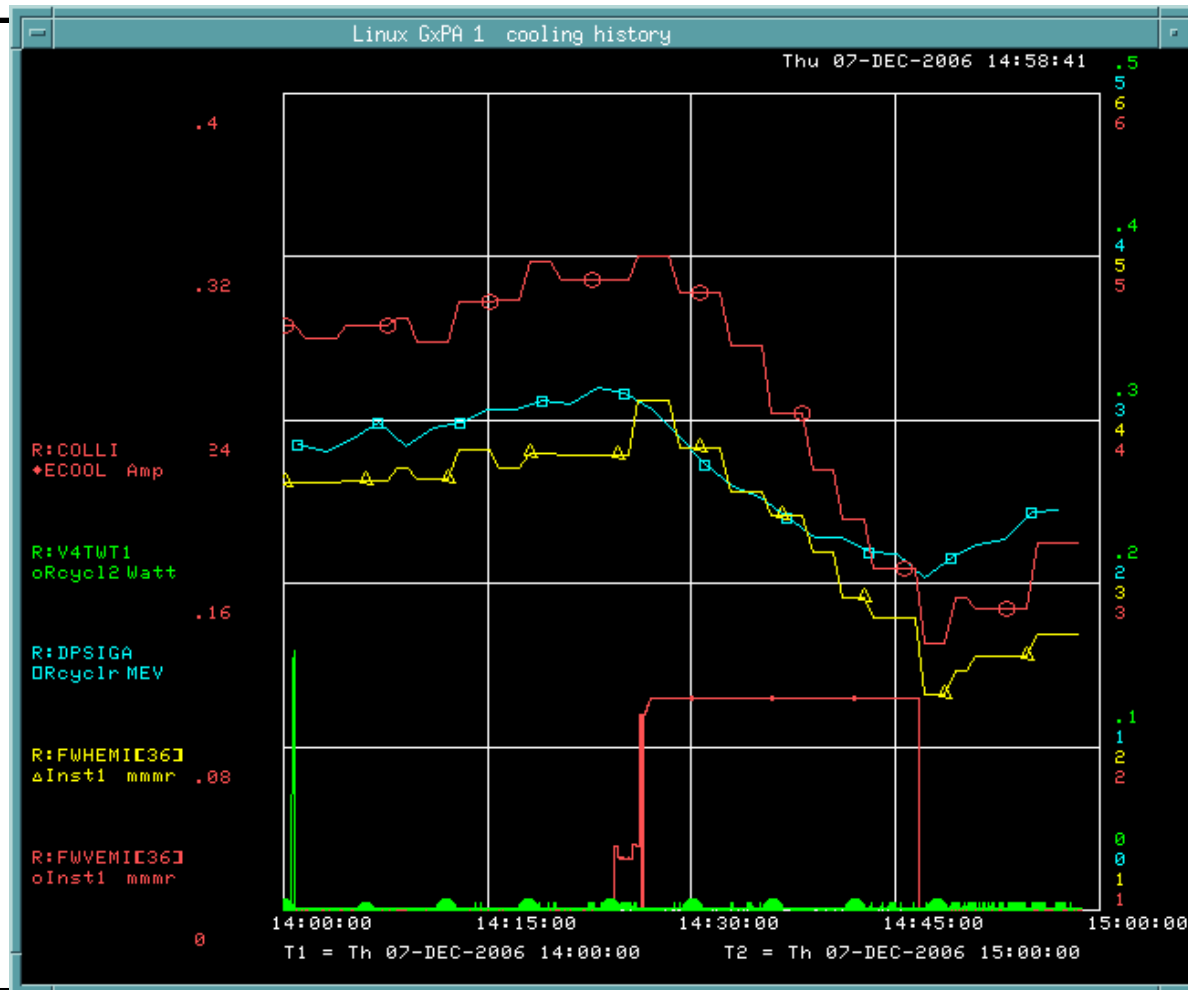


measurements



simulations

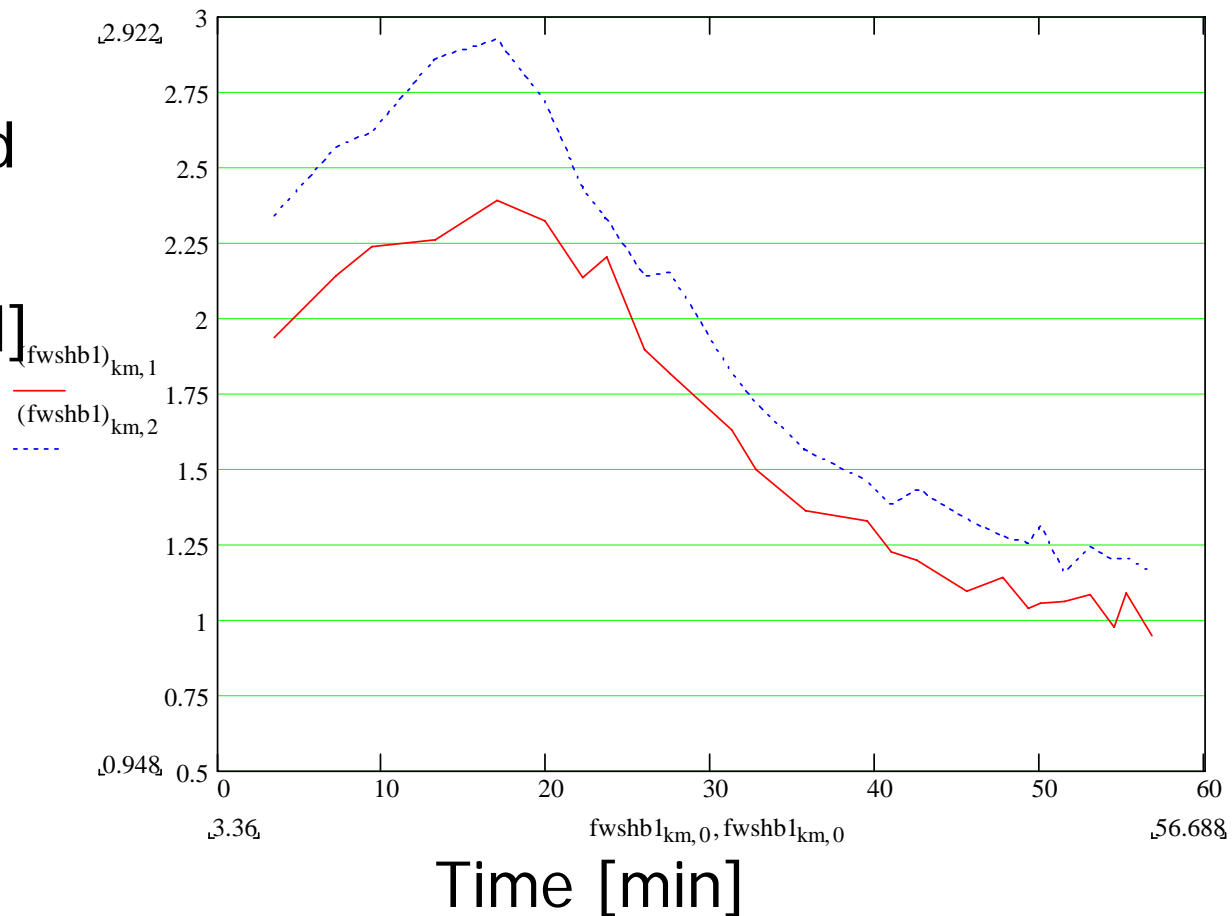
Example of 12.07.06 measurements: History of first set of measurements with expanded anti-proton bunch to 9 micro seconds₂₀ (intensity 160e10 pbars)



Example of FW 12.07.06 measurements for second set of measurements with bunch length of 4.3 micro sec

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95%
normalized
Emittance
[mm mrad]



12.07.06 diffusion/cooling measurements

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1. High-intensity (160×10^{10} pbars):

1.1 With the pbar beam expanded to 9.1 microsec:

- a) - Diffusion rate (stochastic cooling off, electron beam off, dampers on)
- b) - Electron cooling rate (100 mA, on axis; stochastic cooling off, dampers on).
- c) - Diffusion rate of an electron-cooled beam (stochastic cooling off, electron beam off, dampers on)

1.2 With the pbar beam compressed to 4.3 microsec ('dense' beam)

- a) - Diffusion rate (stochastic cooling off, electron beam off, dampers on).
- b) - Electron cooling rate (100 mA, on axis; stochastic cooling off, dampers on).

2. Low-intensity (50×10^{10} pbars):

- Two sets of diffusion measurements and two sets of cooling were recorded. For each type, one was with the damper on and another with the damper off.

Standard measurements were repeated many times during
December 2006 – March 2007.

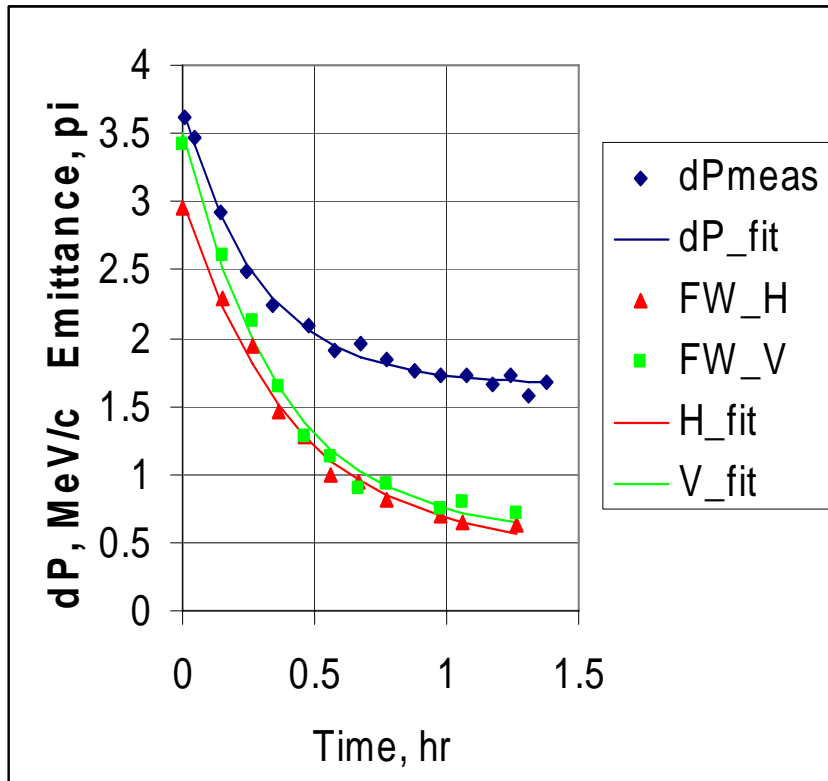
Available data was analyzed.

In simulations, we tried to benchmark measurements of:

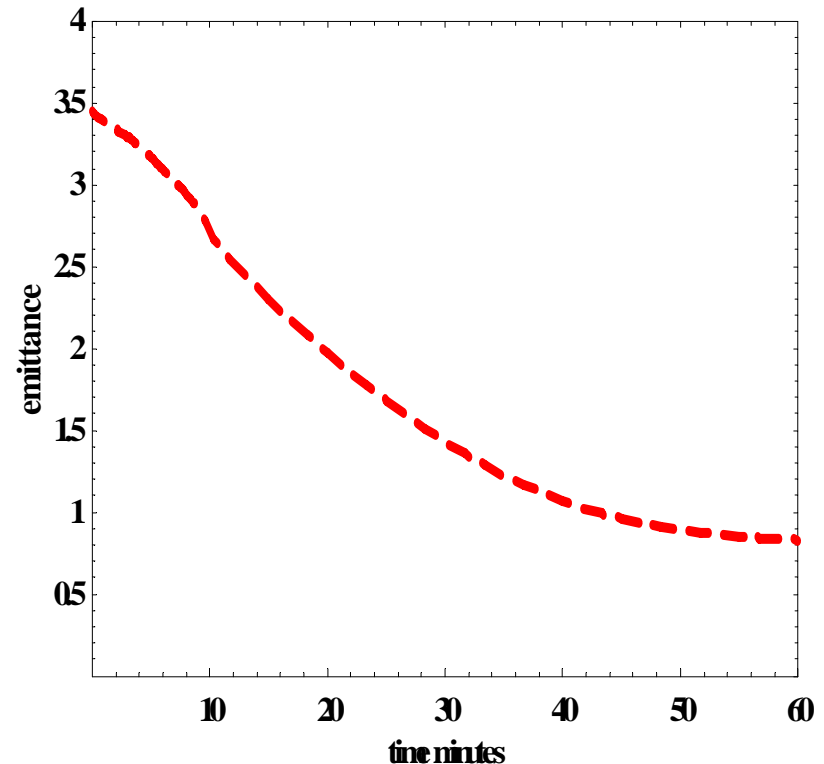
Transverse emittance based on FW.

Longitudinal momentum deviation based on Schottky.

1. For parameters of electron beam which fit measured longitudinal friction force one gets good agreement between measured (FW) and simulated transverse cooling **but in this case longitudinal cooling in simulations is overestimated** (August 2006 data).²⁴

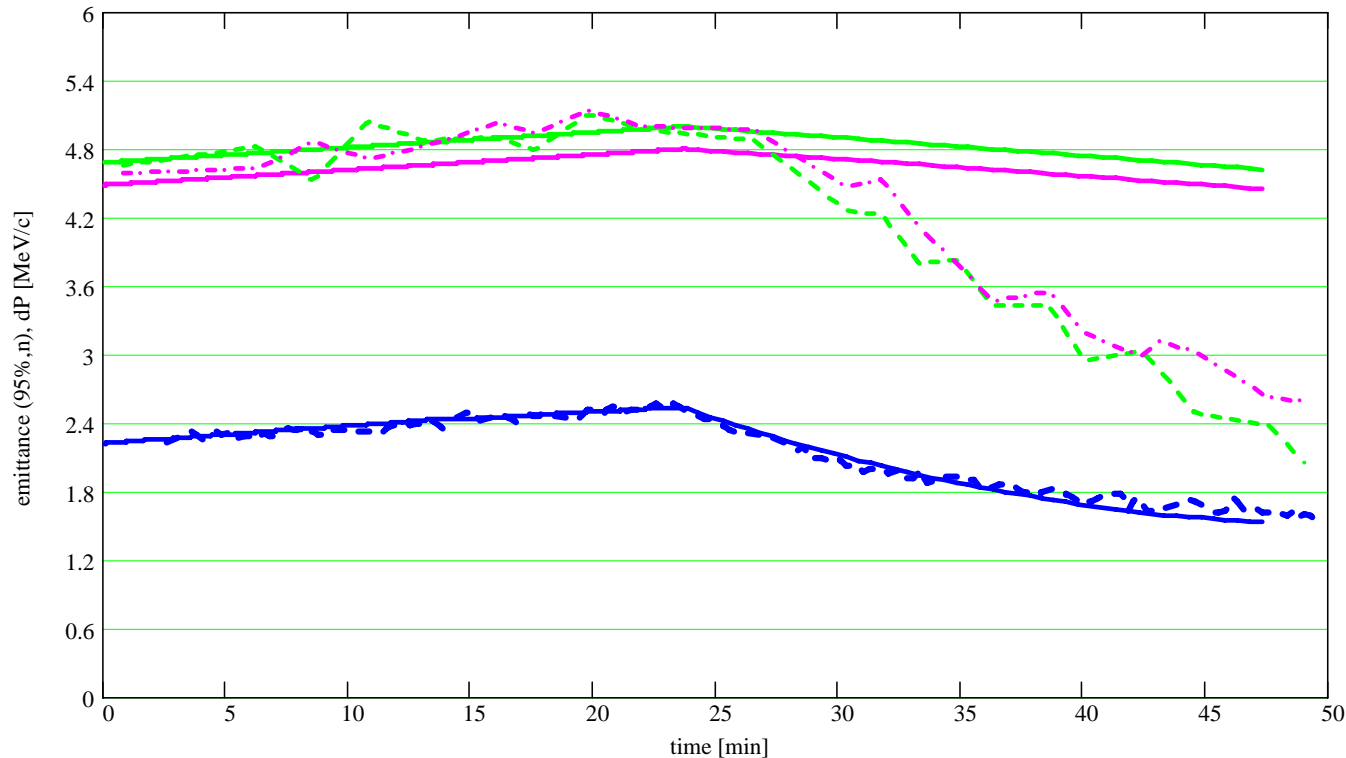


measurements



simulations

2. With addition of transverse velocity gradient – agreement for longitudinal cooling was achieved **but this resulted in disagreement with transverse cooling measurement with FW** (12.20.06 data).

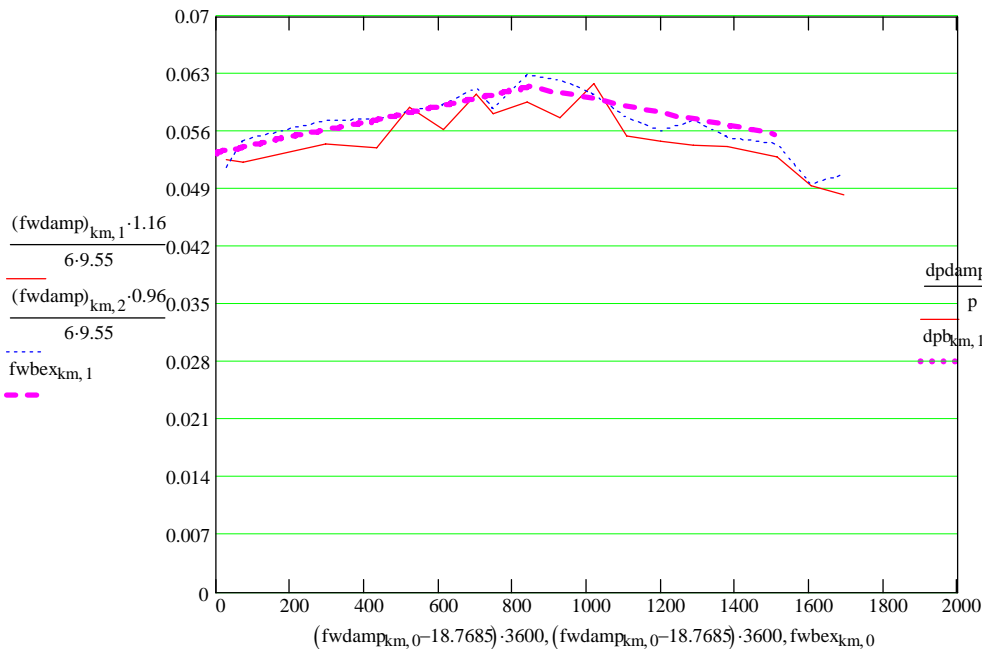


H & V 95% norm.
emittance [mm mrad],
solid lines – simulations
dash – measurements
With FW.

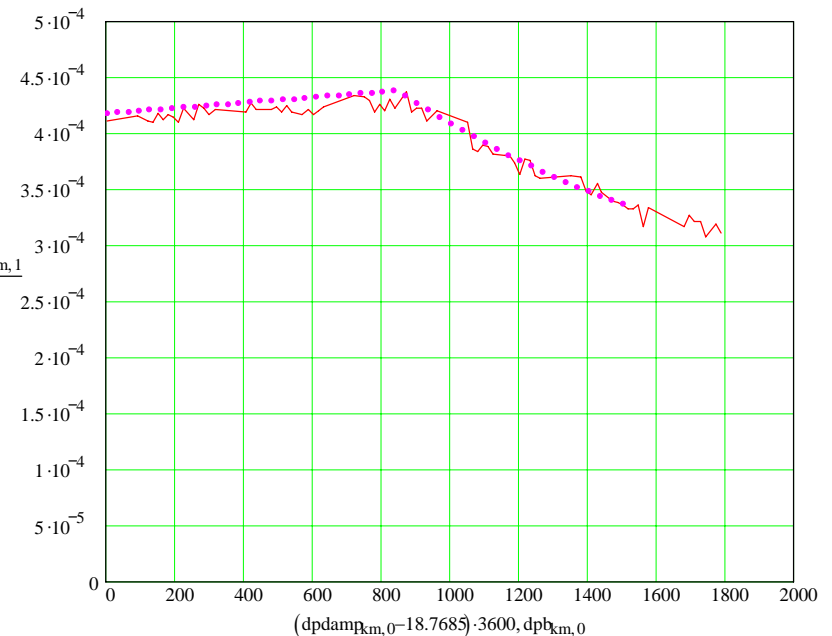
Rms momentum
deviation dp [MeV/h]
solid line – simulation
dash – measurement
with Schottky

3. With addition of transverse velocity gradient and 2m dispersion in the cooling section (02.24.07 data)

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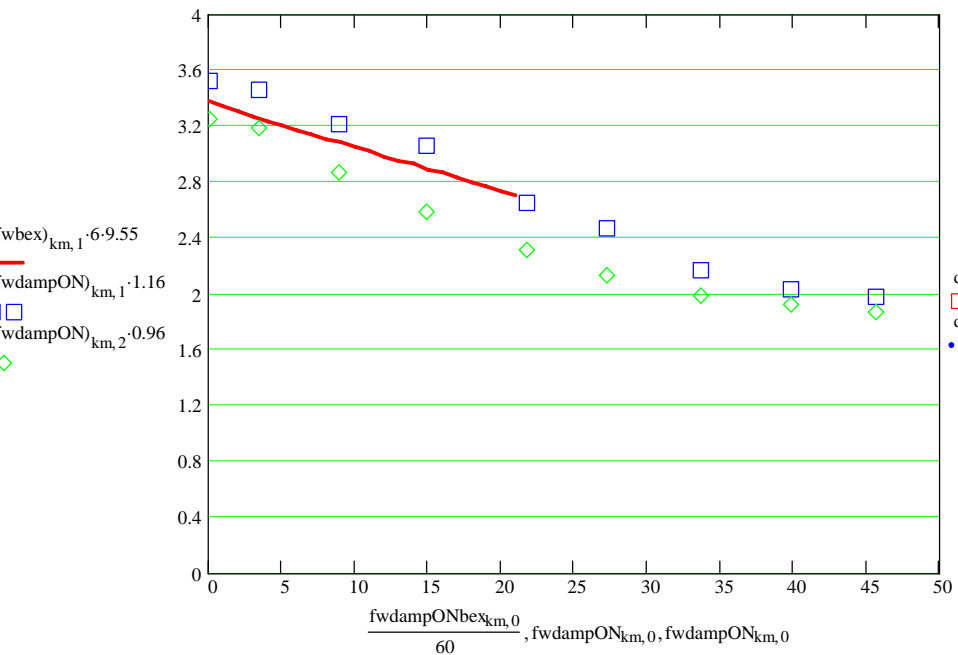
Emittance (rms unnormalized) vs time [sec]



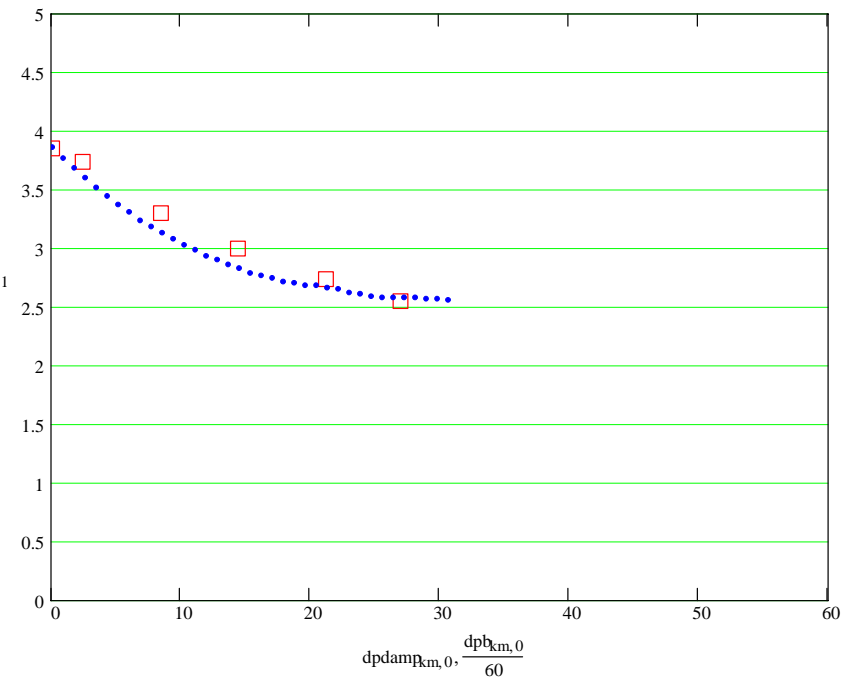
Rms dp/p vs time [sec]

3. High-intensity data reported at RuPAC06. With velocity gradient and dispersion in the cooling section

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Emittance (95% norm.) vs time [sec]



dp [MeV/h] vs time [sec]

Diffusion/cooling - Summary

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Parameters of electron beam – found by fitting measured longitudinal friction force.

1. If dynamic simulations are done without transverse velocity gradient and with zero dispersion, then simulated transverse cooling agrees with transverse measurements based on FW but longitudinal cooling in simulation is significantly stronger than measured.
2. If transverse velocity gradient is introduced, one can match measured longitudinal cooling but this strongly reduces transverse cooling so that measured transverse cooling (FW) is much stronger than in simulations.
3. If in addition to velocity gradient one introduces redistribution of cooling rates in cooling section (for example, 2m dispersion) then one can have reasonable agreement both for the longitudinal and transverse cooling – both for low-intensity and high-intensity diffusion/cooling measurements. However, dispersion in cooling section is much smaller.

Diffusion/cooling – Summary (continued)

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We have disagreement between simulation and measurements.
We cannot reproduce measured transverse and longitudinal cooling simultaneously.

Possible reasons (A. Shemyakin):

1. Incorrect interpretation of measurements:
 - Longitudinal cooling – based on Schottky
 - Transverse cooling - based on FW
 - Transverse cooling based on Schottky shows much less cooling than based on FW.
2. Contribution of magnetized cooling?
3. Redistribution of cooling rates in cooling section.

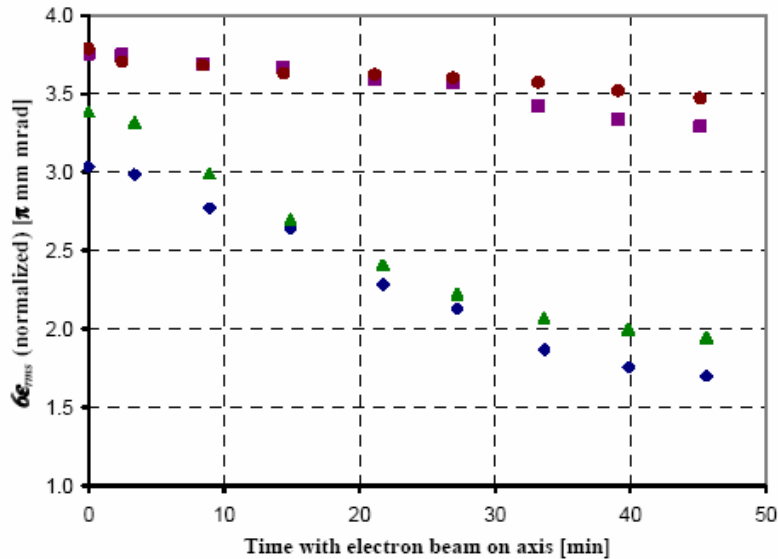


Figure 1: Emittances evolution with the electron beam on axis, 100 mA and stochastic cooling off. Blue diamonds and green triangles are the horizontal and vertical emittances from flying wire measurements. Brown circle and purple squares are the same emittances but measured with a 1.75 GHz Schottky detector. $N_p = 188 \times 10^{10}$ antiprotons, bunch length = 6.1 μ s.

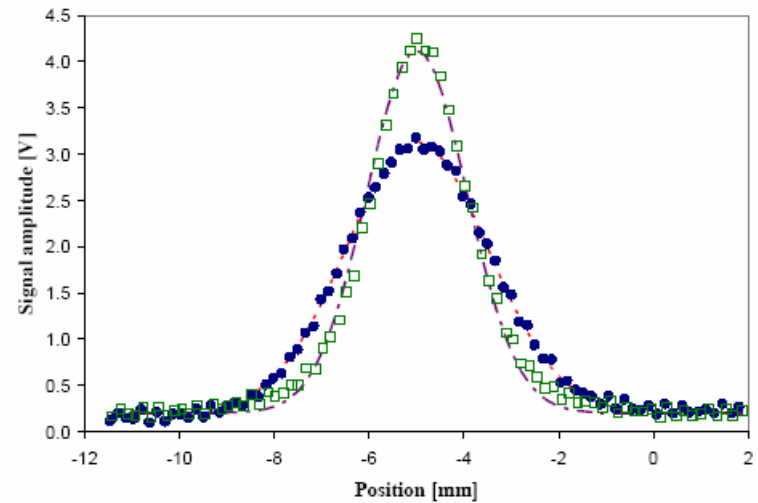
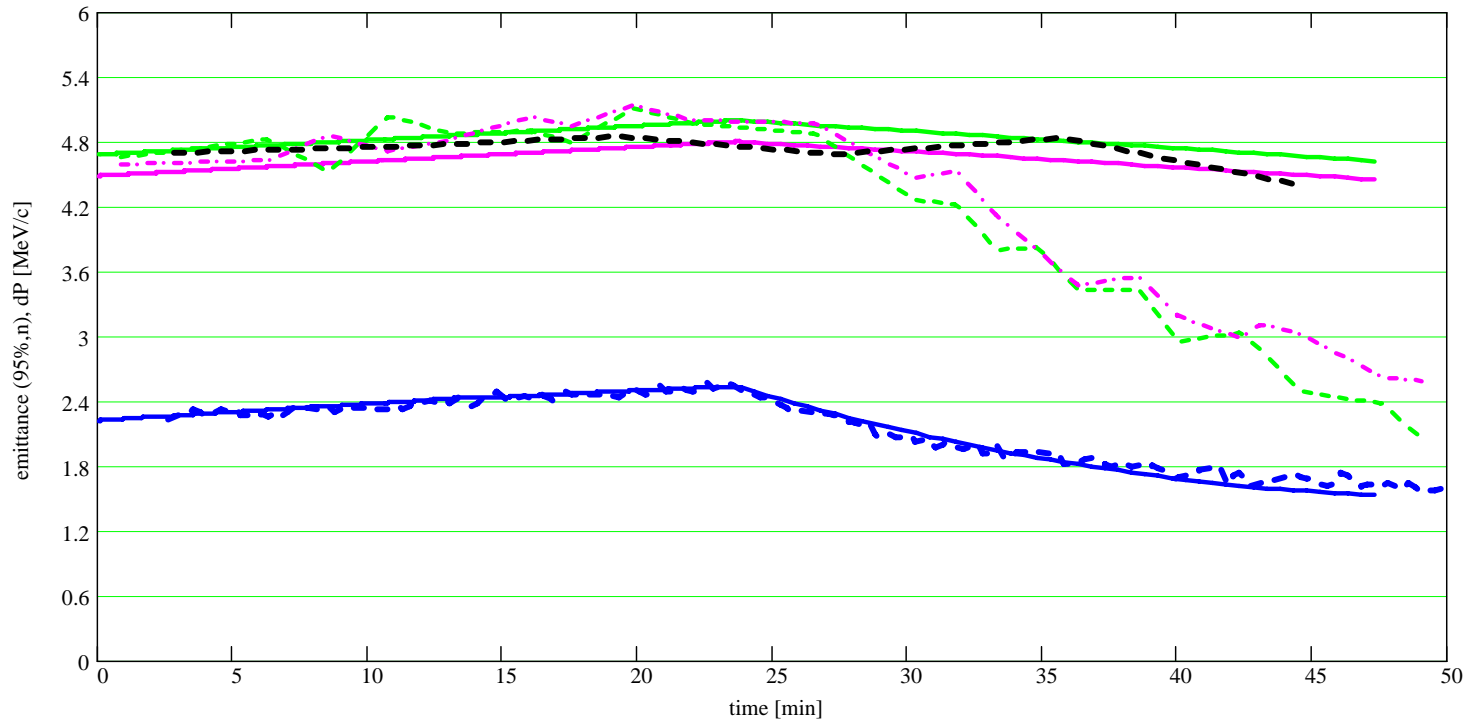


Figure 2: Horizontal antiproton beam profiles before (blue circles) and after (green squares) 60 minutes with the electron beam at 100 mA and on axis. The dotted lines are the best Gaussian fits to the data (with no background subtraction). $N_p = 135 \times 10^{10}$ antiprotons, bunch length = 6.5 μ s (kept constant)

12.20.06 Data: measurement of transverse emittance with Schottky - black dash line

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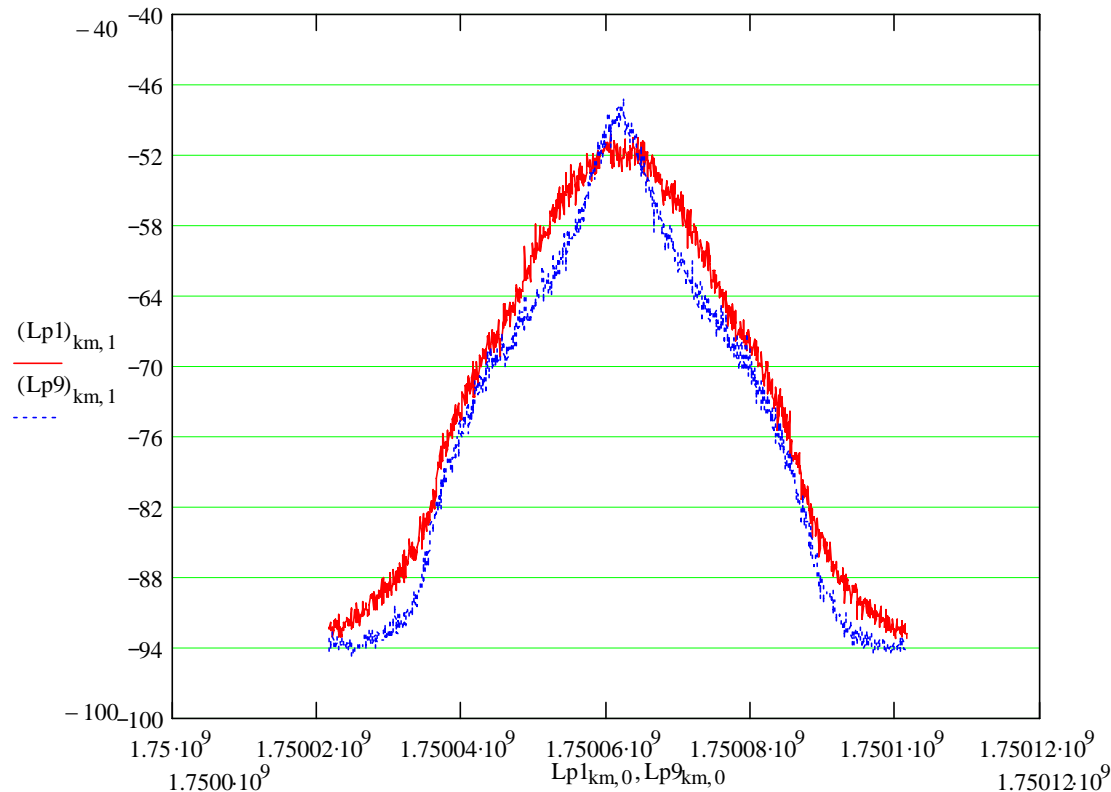


simulations actually agree with measurements both for longitudinal and transverse cooling if compared with both measurements done with Schottky.

Evolution of distribution under cooling and diffusion

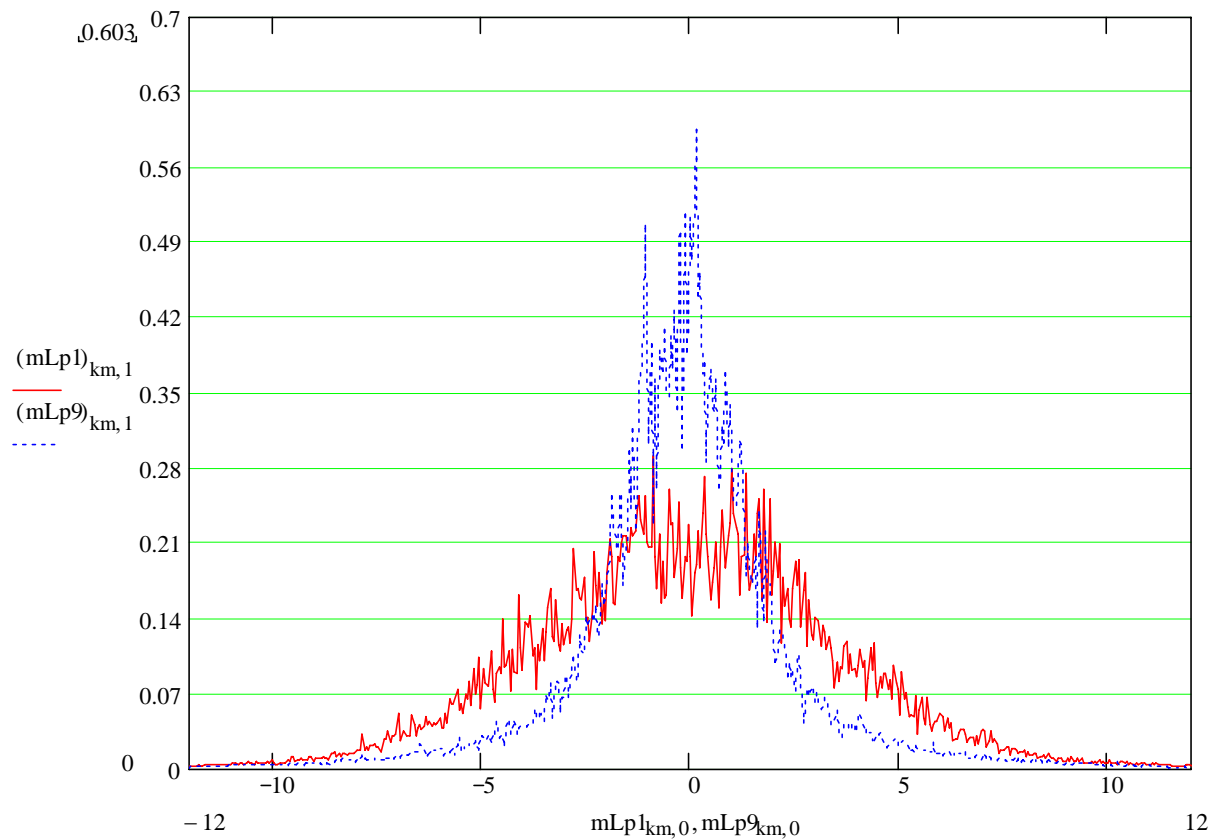
Longitudinal distributions under electron cooling and diffusion (Log scale in dB vs frequency)

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Longitudinal distributions under electron cooling and diffusion (linear scale)

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SUMMARY

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We have very good progress since last year:

1. Good understanding/benchmarking of friction force.
2. Good understanding of measured dependence of friction force on beam current.
3. There is still some uncertainty in benchmarking of dynamic simulations for transverse and longitudinal cooling.

3.1 In principle, since remaining disagreement between dynamic cooling simulations and measurement maybe related to Recycler's electron beam characteristics and specific's of the cooling section, or, perhaps, measurement interpretations, one can state that observed disagreement is not critical.

3.2 On the other hand, since RHIC-II simulations heavily rely on this cooling dynamics predictions, resolving observed differences in Recycler's cooler would be very useful.